THERMAL CONDUCTIVITY OF MEATS

A THESIS

Presented to

The Faculty of the Graduate Division

by

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In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

Georgia Institute of Technology

March, 1967

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ACKNOWLEDGMENTS

The author would like to express his sincere appreciation to all those who made this work possible. In particular, he would like to thank Dr. J. E. Sunderland, his advisor, whose advice and encouragement were invaluable. Further, he would like to thank Dr. W. W. Graham III and Dr. G. T. Colwell for their advice and service on the reading committee. Also, a special note of thanks is extended to Mr. J. E. Hill for his comments and advice.

The author would like to express his gratitude for the Public Health Research Grants EF 00102-03 and EF 00102-04 from the Division of Environmental Engineering and Food Protection which provided partial support for this investigation. He is also indebted to the National Science Foundation for funds making his graduate study possible.

Finally, the author would like to express his sincere appreciation to his wife, Marcia, and his parents, Mr. and Mrs. J. Leitman, without whose love, encouragement, and guidance this work would not have been possible.

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SUMMARY

Measurements of thermal conductivity were made on frozen and fresh beef, pork, veal, and lamb in the temperature range 0 to 150°F. The beef samples were obtained from inside round of canner and cutter grade beef; the other samples were obtained from premium grade legs of pork, veal, and lamb. The data were obtained in order to determine the dependence of conductivity on temperature, moisture content, and direction of heat flow (perpendicular and parallel to the grain of the meat).

The method used was essentially the same as that used by Hill (5), which was based on one-dimensional steady heat flow through the sample. The samples were slabs approximately 9 inches in diameter and from 1 to 1-1/2 inches thick. The plate temperatures were controlled separately by passing ethylene glycol solutions at constant temperature through copper coils which had been soldered to the back of the plates. A differential thermopile was used to measure the temperature difference across the sample, and a specially constructed heat meter was placed with the sample between the "hot" and "cold" plates to measure the rate of heat transfer through the sample. The entire assembly was surrounded by insulation and enclosed in polyethylene. Fourier's one-dimensional heat conduction equation was used to calculate the thermal conductivity.

For each type of meat, measurements were made on one sample with the heat flow parallel to the grain of the meat and on another sample with the heat flow perpendicular to the grain. The moisture content was approximately the same for both samples in each case. All of the meats

exhibited the same dependence of conductivity on temperature; that is, the conductivity varied inversely with temperature in the frozen region (0 to 22°F), and increased slightly with temperature in the unfrozen region. A comparison of the data of this investigation with that obtained by previous investigations indicated that the conductivity increases with increasing moisture content. In the frozen region, the conductivity of the samples measured parallel to the grain was higher than the conductivity measured perpendicular to the grain. For beef, the conductivity measured parallel to the grain was 8 per cent higher than the conductivity measured perpendicular to the grain. The corresponding differences for pork, veal, and lamb were 10, 8, and 14 per cent, respectively.

The conductivity values of the beef sample measured parallel to the grain were compared with values that were predicted by a previously proposed model. The model predicted the conductivity as a function of moisture content for lean beef with a moisture content of 60 per cent or higher, where the heat flow was parallel to the grain. The experimental values compared very well in the frozen region with the predicted values. The greatest difference was about 2 per cent. This model can certainly be a valuable tool in predicting the thermal conductivity of beef.

CHAPTER I

INTRODUCTION

Statement of Intent

It was the intention of this investigation to measure the thermal conductivity of beef, pork, veal, and lamb in the temperature range 0 to 150°F. The dependence of thermal conductivity on temperature, moisture content, and direction of heat transfer (perpendicular and parallel to the grain of the meat) was determined.

Purpose

Knowledge of the thermal conductivity of meat is becoming more important with the rapid increase in the amount of meat and meat products being frozen, particularly since this increase has been accompanied by a strong interest in faster freezing rates. Reliable data are needed for the thermal conductivity of meat which is to be frozen in order to aid in the design of equipment and in predicting its performance under varying conditions. In addition, data are needed for analytical studies of transient processes involving heating, cooling, or dehydrating meats, as in the freeze-drying process; as well as for studies involving the effects on freezing rate of physical factors such as temperature, velocity, and properties of the heat transfer medium, and shape, size, packaging, initial temperature, and structure of product.

Survey of Previous Investigations

Data on the thermal conductivity of meats is limited and, to some extent, conflicting. The moisture content, fat content, and cut of meat are frequently omitted, as well as specific test conditions such as temperature, temperature difference, and direction of heat flow with respect to the meat fiber. In addition, most investigations have covered only a limited temperature range.

Previously reported data on the thermal conductivity of meat are presented in Table 1. It can be seen that the majority of the previous investigations were concerned with beef. Lentz (6), Hill (5), and Cherneeva (4) reported data on the conductivity of beef measured in a direction perpendicular to the grain. These data were obtained using different methods and from samples taken from different cuts of meat at different moisture and fat contents. Lentz (6), Miller (7), and Hill (5) reported data on the conductivity of beef measured in a direction parallel to the grain. Here again, the data were obtained using different methods and from samples taken from different cuts of meat at different moisture and fat contents.

It is expected that the conductivity increases with increasing moisture content. However, the data reported by Lentz, Hill, Miller, and Cherneeva for both directions of heat flow disagree somewhat in this respect. Additional data at other moisture contents will certainly increase the understanding of the dependence of thermal conductivity on moisture content.

Miller and Sunderland (17) present a mathematical model for predicting the thermal conductivity of beef in a direction parallel to the fiber as a function of moisture content. The model predicts values of conductivity which are in excellent agreement with the data reported by Miller (7) and Hill (5), but predicts values 11 per cent below the data reported by Lentz (6). Because of this disagreement, it was felt that additional data were needed to confirm the validity of the model.

It was difficult to make a conclusive comparison of data obtained by different investigators due to the different types of apparatus used and the various kinds of meat available. In addition, the data might have been influenced by differences in the methods used to freeze the samples prior to the conductivity measurements. This investigation provided additional data on the thermal conductivity of beef and pork and previously unavailable data on the conductivity of veal and lamb, in hopes of furthering the understanding of the dependence of thermal conductivity on temperature, moisture content, and direction of heat flow.

CHAPTER II

EXPERIMENTAL INVESTIGATION

Thermal Conductivity Determination

Methods of Measuring Thermal Conductivity

The method used in this investigation for determining thermal conductivity was the same as that used by Hill (5). Before adopting this method, Hill conducted an extensive survey of methods previously used. He discussed the more interesting methods in his thesis, along with the advantages and disadvantages of each for measuring the thermal conductivity of beef. A very brief review of these techniques will be presented in this section.

Transient Method--Shenhav (10). Shenhav presents a rapid method for determining the thermal conductivity of insulating materials. The method involves measuring a one-dimensional transient temperature distribution in a slab. The data are approximated by polynomial expansions which are substituted into the transient heat conduction equation. The resulting equation gives an expression for the thermal conductivity of the material within the range of temperature measured.

Method for Poor Conductors--Zierfuss (11). Zierfuss presents a method for the rapid determination of the thermal conductivity of poor conductors. The method involves bringing a small sample into contact with a hot copper bar and recording the temperature developed at the interfacial contact. With the thermal properties of the copper and the density and specific heat of the sample known, the thermal conductivity is determined from the theoretical equation for two semi-infinite bodies of different temperatures which are held in ideal thermal contact.

Guarded Hot Plate Method (12). This method is the standard of the American Society for Testing Materials. The standard apparatus consists of a central resistance heater, two unknown but identical samples, and two cooling plates on the other sides of the samples. By measuring the energy input to the heater, the areas of the test sections in contact with the heater, the thickness of the test sections, and the temperature drop across the test sections, the conductivity can be determined from Fourier's steady one-dimensional heat conduction equation.

Thin Heater Method. Hager (13) describes a variation on the guarded hot plate method. The heater used is a rectangular sheet of stainless steel foil. Sample slabs are placed against opposite sides of the heater and the apparatus is placed in a plastic bag and immersed in a bath having a constant and uniform temperature. The conductivity is then determined as in the guarded hot plate method.

Method of Schröder (14). This method, like the guarded hot plate method, is based on Fourier's steady one-dimensional heat conduction equation. The basis of this method is the maintenance of a fixed temperature between the two ends of the sample by immersing the ends in two boiling liquids with suitable boiling points. The time is measured for a given quantity of heat to flow through the sample. The quantity of heat is measured indirectly by calculating the amount of heat required to evaporate a certain amount of the liquid at the "cold end" of the sample, which is collected as condensate.

Line Source Method. Underwood and McTaggart (15) describe this transient method of measuring the thermal conductivity of plastics. If heat is supplied to an infinite solid at a constant rate along a line, the temperature rise with time of a point near the line is a function of the rate of energy input and the properties of the solid.

Heat Flow Meter Method. The method of measuring the thermal conductivity of beef selected by Hill (5) and used in this investigation is a steady state method, very similar to one described by Pelanne and Bradley (16). As in the guarded hot plate method, the heat flow is one-dimensional and is described by the Fourier equation. The conductivity is calculated from the temperature difference across the sample, thickness of the sample, and the heat flow. In contrast to measuring the energy input to a heater, the heat flow is measured by allowing it to pass through a sample of known conductivity as well as the unknown sample. The known sample is a heat meter, and along with the rest of the apparatus, will be more fully described in the next section.

Instrumentation and Equipment

Although the apparatus used in this investigation was essentially the same as that used by Hill (5), it was substantially rebuilt and a number of refinements were made. The majority of the refinements were made in order to facilitate the process of obtaining data or to increase the range of the apparatus to include average meat temperatures up to 150°F.

Heat Flow. The meat sample and heat meter were placed between a hot and cold plate as shown in Figure 1. The temperatures of these plates

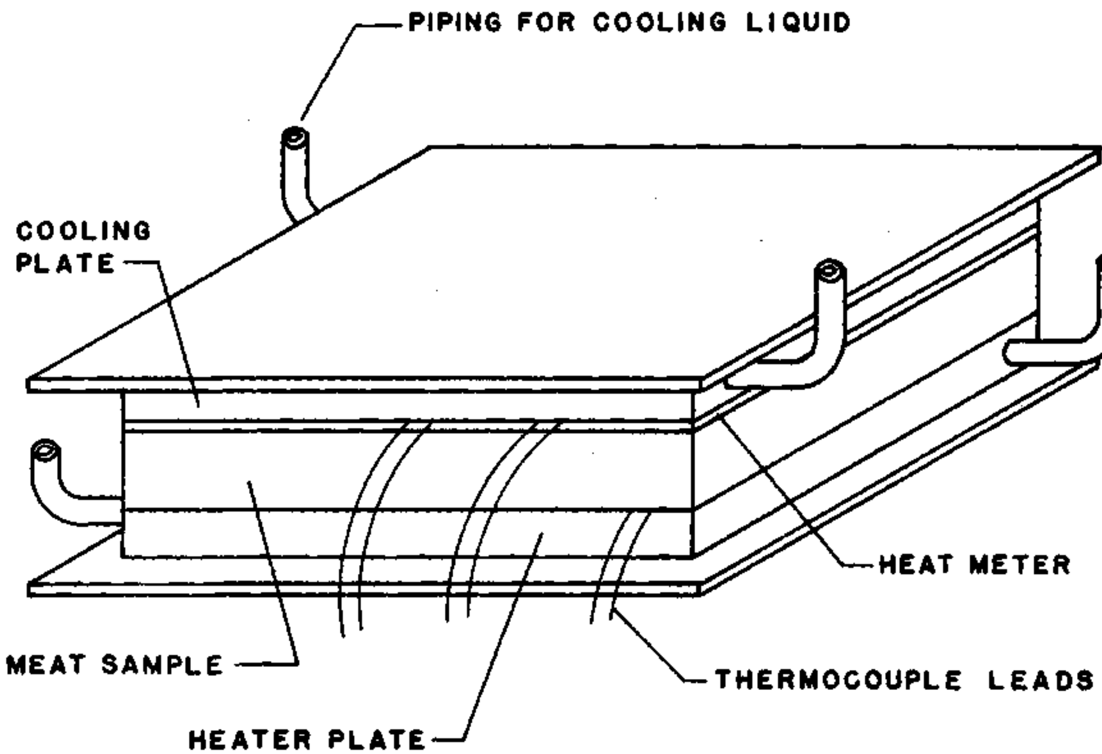


Figure 1. Hot and Cold Plate Assembly.

were controlled separately by passing ethylene glycol solutions through them. The entire assembly was held together by one-inch bolts passing through the four corners of the extreme top and bottom plates (cover plates).

The construction of both plates was identical and is shown in Figure 2. The heat transfer plate, or the plate adjacent to the sample, was a copper plate 1/4 by 9 by 9 inches. The coil structure was made separately and then soldered to the top of the copper plate with lead solder. The spaces between the coil pipes were completely filled with solder to insure good contact. The coil was made of 3/4-inch copper pipe, whose pieces were cut at 45° at the end and silver-soldered together. This method of joining the pieces was preferred over the use of fittings, in order to conserve space. The reason for choosing the flow pattern shown was to try to obtain a uniform temperature distribution on the plate. The steel cover plate was held in place by 1/4-inch brass bolts which were soldered into the top or back of the surface plate. The sides were closed by attaching 1/8-inch flexible rubber with strong glue to the edges of the copper and cover plates. The space between the top of the coils and cover plate was filled with fiberglas insulation. The surface of the copper plate was smoothed with emery paper and painted with a light coat of dull black paint.

Plate Temperature Control. The temperatures of the ethylene glycol solutions passing through the plates were controlled by a constant temperature bath system (Figure 3). The two anti-freeze solution containers held 10 gallons and were surrounded by 2-1/2 inches of blanket insulation. Both the hot and cold plate baths contained a

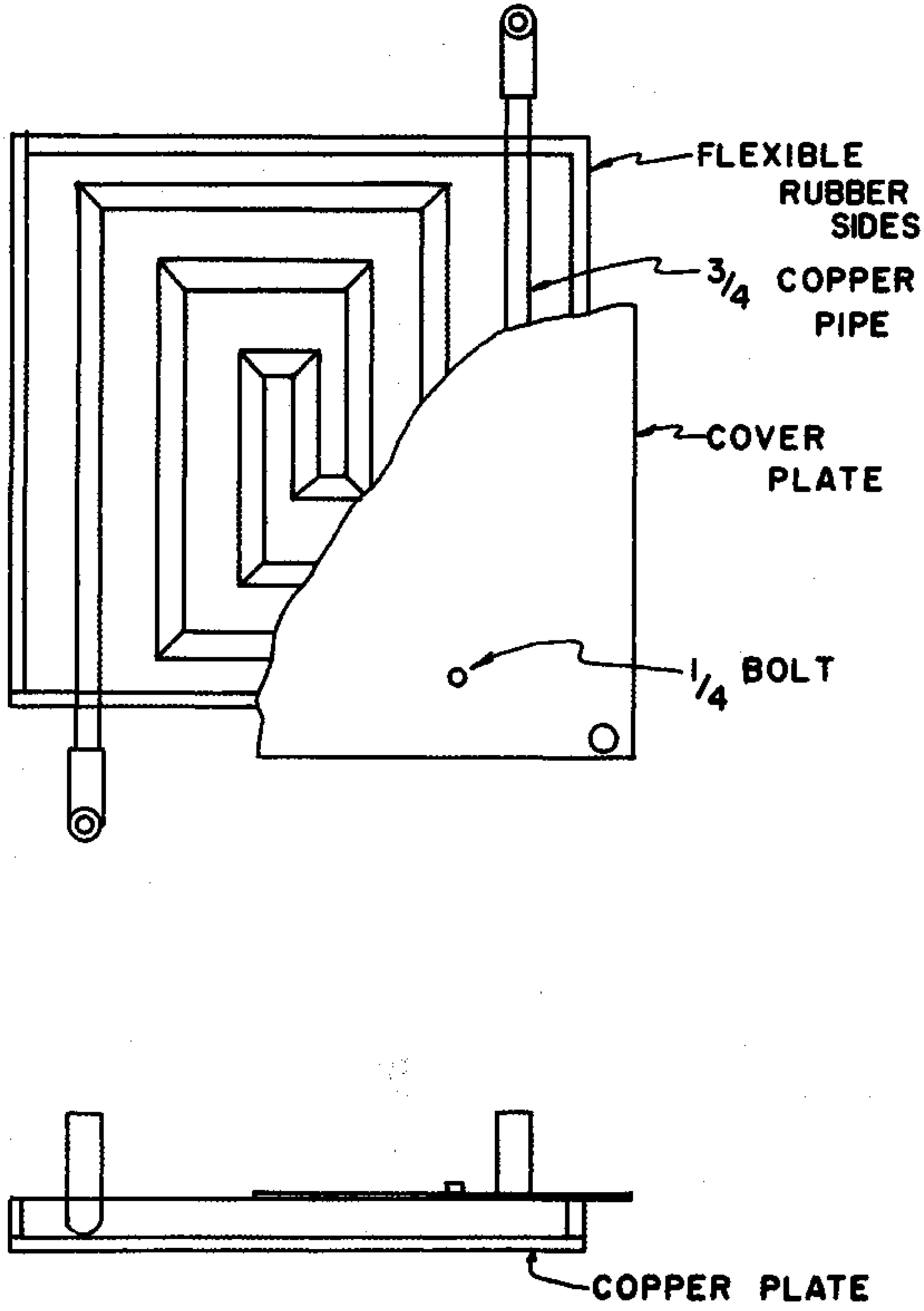


Figure 2. Cooling and Heating Plate.

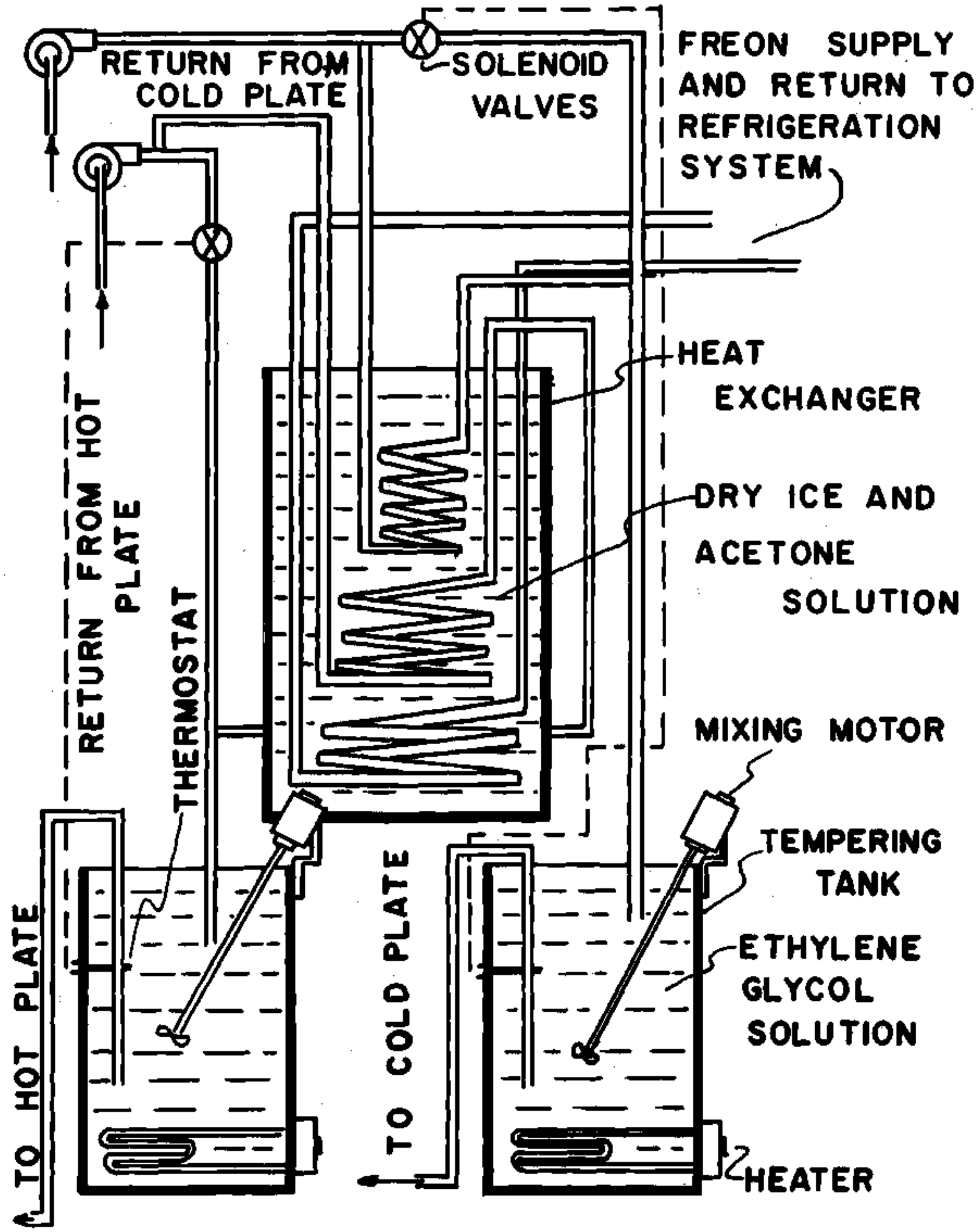


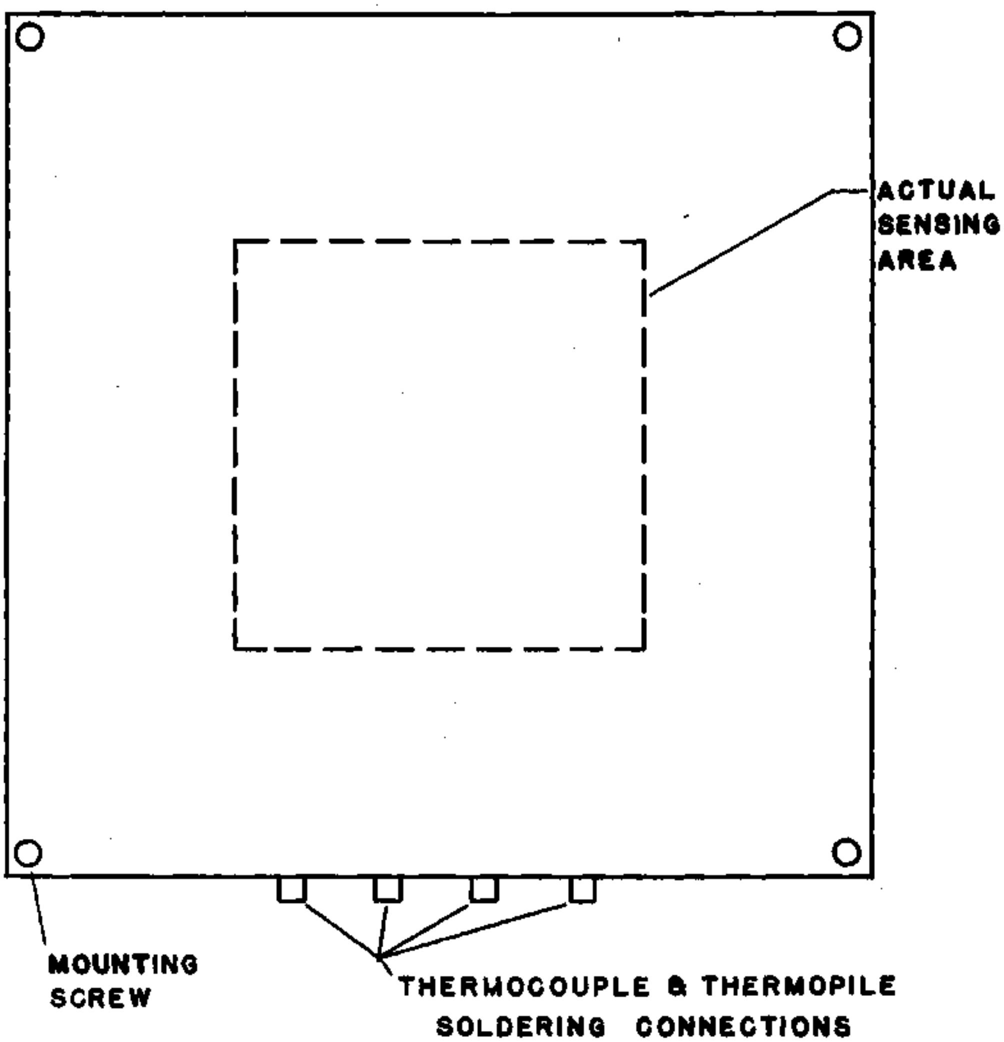
Figure 3. Diagram of Constant Temperature Baths.

variable output 2500-watt immersion heater. These heaters were set for a constant power output depending on the tank temperatures required. The stirring motors kept the solutions completely mixed. The pumps used for circulating the anti-freeze mixtures were Oberdorfer 1/12 horsepower model number 5180 centrifugal pumps, which were driven by 1/3 horsepower electric motors. They were placed in a position to pull the constant temperature liquids from the tanks through the plates rather than pumping the liquids to the plates. This allowed the uniform temperature fluids to pass directly to the plates without the addition of heat from the pumps.

The thermostats operated the solenoid valves to deflect the return flow through cooling coils in the heat exchanger when the tank temperatures were higher than the thermostat settings. The thermostats were Fenwall immersion thermoswitches number 17100-0. The solenoid valves were ASCO valves number 8030A1. The cooling tub was a 20-gallon container of acetone and dry ice which was surrounded by 2-1/2 inches of blanket fiberglas insulation. The dry ice was used only to supplement the refrigeration unit, which was a Copeland model number CSAL-0100-CAB-001 which used refrigerant 12.

Heat Meter. The heat meter was a specially designed model number T200-3 manufactured by the Beckman and Whitely Company. The design is shown in Figure 4.

The multi-junction thermopile elements were arranged in a thin bakelite plate. The thermopile consisted of a series of silver-constantan thermocouples which were positioned so that one set of junctions (cold junctions) was in a plane adjacent and parallel to one face



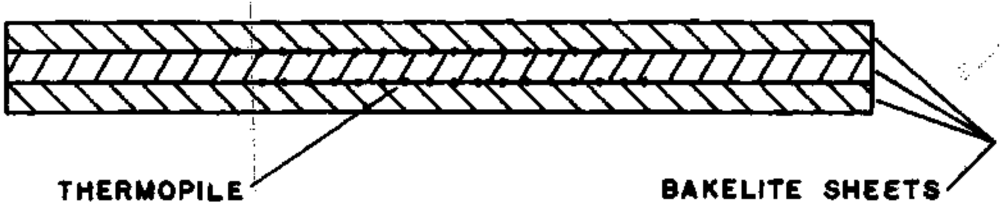


Figure 4. Heat Flow Transducer.

of the plate, and the other set of junctions (hot junctions) was in a plane adjacent and parallel to the other face of the plate. Heat flow through the plate generated an electromotive force due to the difference in temperature of the hot and cold junctions of the thermopile. The measuring junctions were centrally located in the plate and covered an area of 4 inches by 4 inches. The plate dimensions were 9 inches by 9 inches by 3/64 inch.

The meter was calibrated by comparison with known heat flows, so that with the aid of a correction curve (Figure 5) an output reading could be converted directly into heat flow rate. At 80°F, one millivolt output was equivalent to 5.76 Btu/hr ft °F. Figure 5 allowed for a correction for the temperature-coupled variations in the thermopile output. This curve was supplied with the heat meter. The output of the thermopile was read on a model number 8686 Leeds and Northrup precision portable potentiometer.

Temperature Measurement. The arrangement for measuring the temperature drop across the sample is shown in Figure 6. The thermocouple junctions were all copper constantan, made from Leeds and Northrup 30-gauge thermocouple wire, and attached by a heat welding process with no other metal involved in the junction of the two wires. The ice baths were dewar vacuum flasks containing a mixture of crushed ice and water. The accuracy of the entire system was checked by calibrating against a set of secondary standard mercury-in-glass thermometers. The junctions 1, 2, 3, and 4 were attached to the surface of the copper plate in contact with one surface of the sample and the junctions 1', 2', 3', and 4' were attached to the other side of the sample. The output was magnified

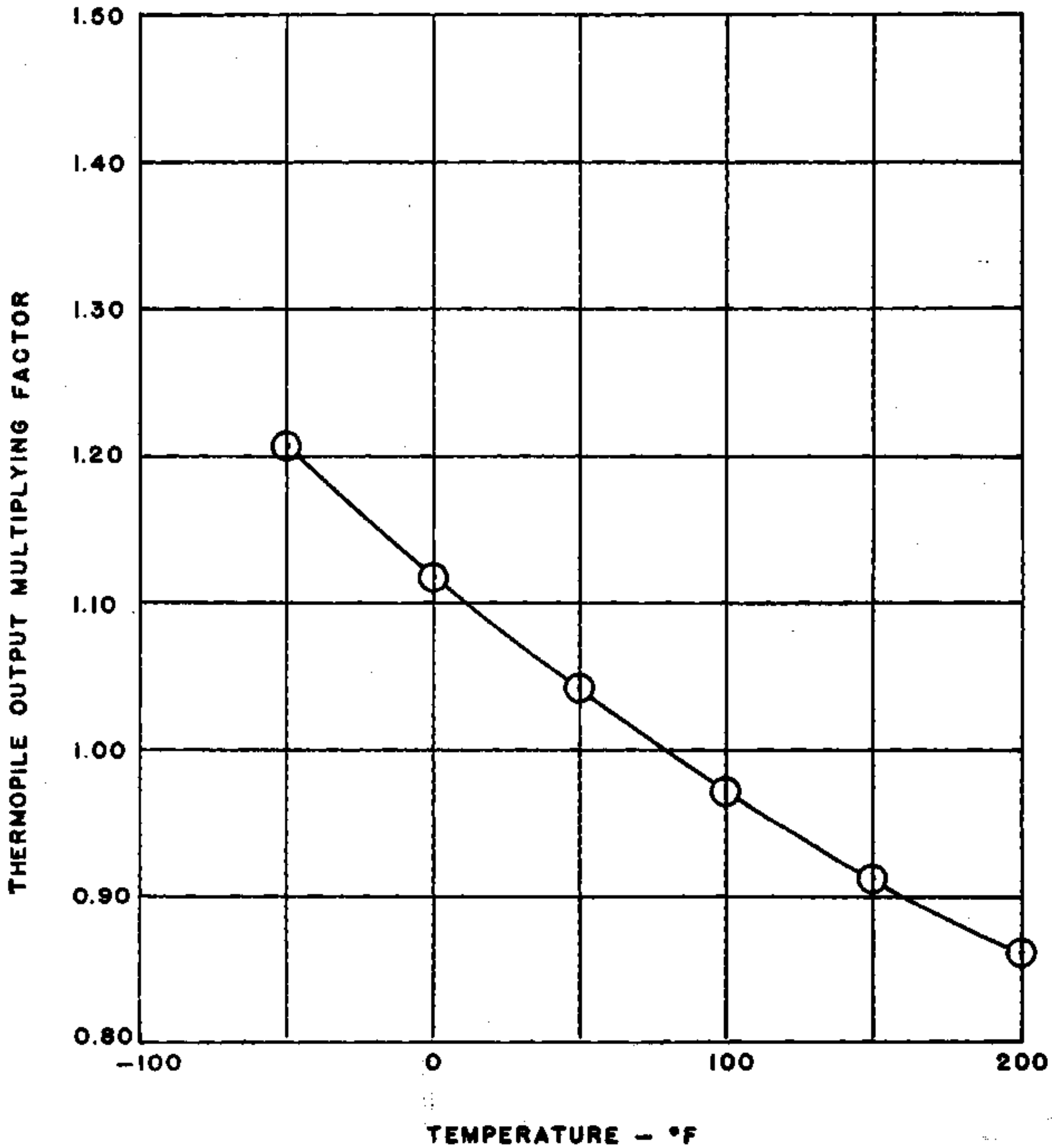


Figure 5. Heat Meter Calibration Curve.

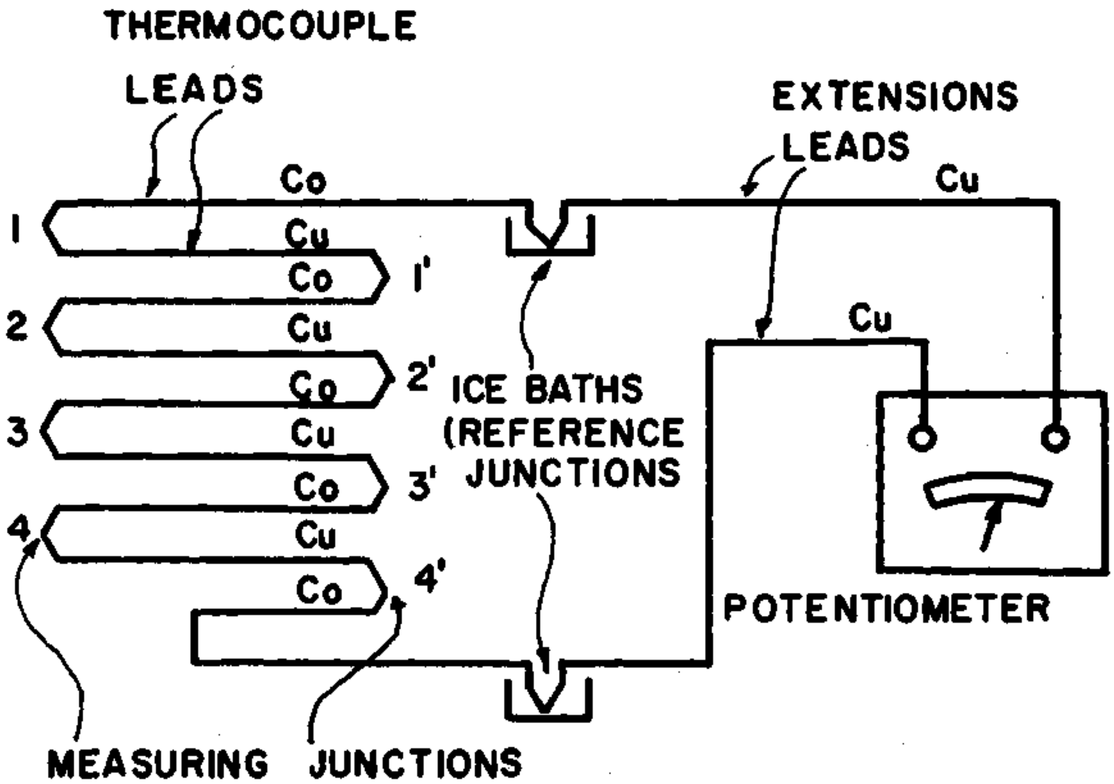


Figure 6. Differential Temperature Measurement.

by the number of couples in series and thus permitted the detection of very small temperature differences. One observation gave the arithmetic mean of the temperature difference sensed by the two groups of four measuring junctions when the total emf was divided by four. A separate thermocouple was attached to one surface in order to indicate the temperature level. The potentiometer used was a Leeds and Northrup model number 8686 precision portable potentiometer.

Experimental Procedure

Sample Preparation. The samples of beef used were taken from the inside round of canner and cutter grade. This type of beef was chosen because it was extremely lean and could be bought in large pieces, enabling good-sized samples to be cut from them. The pork, veal, and lamb samples were taken from the leg portion and all were premium grade. The leg portion was chosen to facilitate obtaining large samples. The meats were cut to approximate sample size, placed in plastic bags to retard dehydration, and frozen for several days in a home freezer. They were then removed and cut on a band saw in order to obtain the samples in slab form. When possible, the samples were cut to an approximate size of 9 inches in diameter and from 1-inch to 1-1/2 inches thick from one slab of meat. When this was not possible, several smaller pieces had to be cut and placed together in order to form the 9-inch sample. The samples were weighed and then refrozen for approximately a day prior to testing.

Conductivity Measurement. The experimental procedure used for measuring the conductivity and determining the moisture content of the samples is as follows:

1. The refrigeration unit was started.

2. The thermopile for determining the temperature drop across the sample and the thermocouple for sensing the temperature level were checked for correct readings by comparison with a set of standard mercury-in-glass thermometers. The thermopile and the thermocouple were attached to the plates of the apparatus.

3. The sample was removed from the freezer and weighed.

4. The surface of the meat was wetted and then placed in the hot and cold plate assembly. The wetting insured good contact at both surfaces of the sample.

5. The corner bolts were adjusted until the sample was held firmly between the plates and there was the same distance across the sample on all four sides. A set of inside calipers used in conjunction with another set of outside vernier calipers was used to measure the distance.

6. The pumps circulating the anti-freeze solution through the plates were started.

7. The thermostats were set at approximately the settings for the first data point.

8. Dry ice was added to the acetone in the heat exchanger, and then again whenever needed to maintain the heat exchanger at a temperature well below the cold plate temperature.

9. Three inches of rigid fiberglas insulation were placed against the four sides of the hot and cold plate assembly. The entire assembly was wrapped with 2-1/2 inches of blanket insulation and then enclosed in polyethylene. Silica gel was placed in the bottom of the

enclosure to keep the insulation dry throughout the tests.

10. Since the thermostats were not marked directly in terms of temperature, they had to be adjusted several times to obtain the correct average temperature level. A temperature drop across the sample of at least 30°F was maintained if possible at all data points. This was not feasible at points near the thawing region.

11. Readings from the heat meter, thermopile, and thermocouple were taken every half an hour until steady state was reached. It was assumed that steady state was achieved when the variation in temperature readings was less than 1°F over a one-hour period. Values were then read every ten minutes for two to three hours, and all the readings were averaged for the calculation of conductivity.

12. All the data points in the frozen region were taken first. They were taken in a random order to make certain that there was no error as a result of approaching all points from either a lower or upper temperature.

13. The plate temperatures were increased and the sample was allowed to thaw completely before the data were taken in the unfrozen region.

14. After all data had been taken, the sample was removed, weighed again, and refrozen.

15. The sample was then placed in a freeze-drying chamber and dried until no change of weight could be detected for a period of several hours. It was removed and weighed.

16. A separate sample was taken from each portion of meat and dried in a freeze-drying chamber in order to determine the moisture

content. Because of the large weight losses incurred at elevated temperatures during the conductivity measurements, it was not possible to accurately determine the moisture content by dehydration of the sample itself.

Experimental Accuracy. The overall accuracy of the experimental apparatus was investigated by measuring the thermal conductivity of a slab of paraffin wax and of a slab of yellow pine perpendicular to the grain, and comparing the results with handbook values. The value for paraffin was 2.1 per cent higher than the handbook value and that for the yellow pine was 3.4 per cent low. These values were considered good, since the handbook values were averages of several conductivity measurements.

Fat Content Determination

Methods of Measuring Fat Content

It was necessary in this investigation to determine the fat content of the meat samples, in order to more completely specify the nature of the meat tested. Before adopting the method used in this investigation to determine the fat content, a survey was made of the various methods for measuring the fat content.

Mehlenbacher (8) classifies the various methods of measuring fat content into three groups as follows:

1. The fat is extracted with a solvent, the solvent evaporated, and the fatty residue weighed. These methods include the Butt, Soxhlet, and Mojonnier methods and are the most reliable as well as the most commonly used. Included in this group is the official method adopted by

the Association of Official Agricultural Chemists and recognized as the standard method for the determination of fat content in meat and meat products. Unfortunately, this method is very long and tedious.

2. The fat is extracted with a solvent, and some physical property of the solution is determined such as refractive index or specific gravity. The change in the property brought about by addition of the fat to the solvent is correlated with fat content. These methods are complicated and involve expensive equipment.

3. The sample is digested to liberate the fat, after which the fat is separated centrifugally and then measured volumetrically. The Babcock and Gerber methods, most commonly used in the dairy industry, are typical of this type. The method used in this investigation is of this group and is a modified Babcock procedure presented by Salwin, et al. (9).

Experimental Apparatus

In the modified Babcock procedure presented by Salwin, et al. (9) and adopted for use in this investigation, the following equipment was specified:

1. Food blender (Waring Commercial Blendor, model number 1001).

2. Torsion balance (Chainomatic, Christian Becher, Inc.).

3. Metal beaker, 1000 ml capacity.

4. Centrifuge or Babcock tester, unheated (Garver Electrifuge, model number 73).

5. Paley-type Babcock cheese bottles, 20 per cent size (Kimble Glass No. 508).

6. Medicine dropper (Glasco Products No. 2020).

7. Dividers (L. S. Starrett Co.).

8. Perchloric acid--acetic acid mixture, prepared by mixing equal volumes of reagent grade glacial acetic acid and reagent grade perchloric acid of 60 per cent strength.

9. Red mineral oil, specific gravity approximately 0.82 at 20°C.

Experimental Procedure

The method presented by Salwin, et al., provided a procedure for the rapid determination of fat content. The tests were of approximately 30 minutes duration each. The procedure was as follows:

1. The sample was comminuted in the blender for approximately 30 seconds.

2. A 9.00-gram weight of the prepared sample was placed in the Paley bottle.

3. Thirty milliliters of the perchloric acid--acetic acid mixture was added to the Paley bottle and the bottle was swirled to mix the contents.

4. The bottle was immersed in a boiling water bath and agitated occasionally during the heating period until the sample was completely digested, which required approximately 12 minutes.

5. The bottle was removed from the bath as soon as digestion was complete and more of the acid mixture was added, as necessary, until the fat column rose in the graduated neck of the bottle.

6. The bottle was centrifuged for two minutes. If, after centrifuging, the fat column extended below the graduated neck of the bottle, more of the acid mixture was added and the bottle was centrifuged for an additional minute.

7. With the aid of a pair of dividers, the fat content was read directly from the length of the fat column in the graduated neck of the bottle.

8. If the reading was greater than 11.0 per cent fat, one drop of red mineral oil was added in the neck of the bottle to clarify the meniscus.

9. The test was repeated twice for a total of three tests for each sample in order to increase the accuracy of the measurement.

Salwin, et al. show that the results obtained by this rapid method is within ± 0.5 per cent fat of the results obtained by the official method of the Association of Official Agricultural Chemists. It should be noted that a more complete discussion of the equipment, procedure, and accuracy of this method is presented by Salwin, et al.

CHAPTER III

PRESENTATION AND DISCUSSION OF RESULTS

Introduction

The results obtained from the current investigation are shown in Figures 7 through 13 and tabulated in Table 2. Thermal conductivity data obtained by previous investigators are presented in Table 1. The conductivity values are plotted as a function of temperature and compared with the results obtained by previous investigators. However, it is difficult to make a conclusive comparison of previous data with the data of this investigation because of the different types of apparatus used and the various kinds of meat available.

In addition, the conductivity values might have been influenced by differences in the freezing rate, freezing temperature, and length of time in frozen storage prior to the conductivity measurements. The thermal conductivity of crystalline solids depends on lattice waves. The lattice wave contribution to the thermal conductivity depends on the type and number of dislocations or imperfections within the crystals, which in turn depends on the freezing conditions. Meryman and Platt (21) and Meryman (20) discussed the influence of freezing rate, freezing temperature, and frozen storage time on ice crystal formation. During freezing, the ice crystals form parallel to and between the meat fibers. The freezing rate affects the crystal size, and hence, probably the type and number of imperfections. Since the ice crystals have a tendency to

Table 1. Thermal Conductivity of Nondehydrated Meats by Previous Investigators

Reference	Material	Per Cent Moisture	Direction of Heat Flow with Respect to Fiber Direction	Temperature °F	Conductivity Btu / Hr °F Ft
1	Beef			-200	0.895
2	Muscle				0.114
	Fat				0.118
4	Beef,	78.5	Perpendicular	32	0.277
	lean			23	0.612
				14	0.779
				-4	0.907
	Beef,	74.5	Perpendicular	32	0.277
	fat			23	0.537
				14	0.692
				-4	0.827
	Beef,	7.0		32	0.118
	fat			23	0.122
				14	0.131
				-4	0.141
	Pork,	76.8	Perpendicular	32	0.276
	lean			23	0.442
				14	0.570
				-4	0.745
6	Beef,	74	Perpendicular	36.5	0.279
	lean,			32	0.2785
	Flank,			23	0.588
	(3.4% fat)			14	0.616
				-4	0.675
	Beef,	75	Parallel	43	0.300
	lean,			35	0.290
	Sirloin,			32	0.284
	(0.9% fat)			23	0.742
				14	0.792
				-4	0.904
	Beef,	9.0		23	0.166
	Udder,			14	0.148
	(89% fat)				
	Pork,	72	Perpendicular	40.1	0.266
	lean,			20.3	0.700
	leg,			-2.2	0.761
	(6.1% fat)			-9.4	0.786
	Pork,	72	Parallel	39.2	0.290
	lean,			16.7	0.822
	leg,			-2.7	0.895
	(6.1% fat)			-10.3	0.919

Table 1. Thermal Conductivity of Nondehydrated Meats by Previous Investigators (Continued)

Reference	Material	Per Cent Moisture	Direction of Heat Flow with Respect to Fiber Direction	Temperature °F	Conductivity Btu / Hr °F Ft
7	Beef,	69.5	Parallel	42	0.185
	lean,			37	0.18
	eye of loin,			24	0.59
	U.S. Good			17	0.60
	Grade			10	0.61
				2	0.62
5	Beef,	76	Perpendicular	46.3	0.257
	lean,			45.8	0.256
	Inside			42.1	0.255
	Round,			36.3	0.252
	Canner and			24.6	0.583
	Cutter			18.9	0.623
	Grade,			16.5	0.635
	(3% fat)			17.0	0.632
				8.6	0.647
	Beef,	76.5	Parallel	46.5	0.232
	lean,			37.5	0.230
	leg,			22.3	0.690
	Inside			18.4	0.701
	Round,			13.0	0.750
	Canner and			0.3	0.796
	Grade,				
	(2.35% fat)				

Table 2. Thermal Conductivity of Nondehydrated Meats by Current Investigation (Continued)

Material	Per Cent Moisture	Direction of Heat Flow with Respect to Fiber Direction	Temperature °F	Conductivity $\frac{Btu}{Hr\ ^{\circ}F\ Ft}$
Veal,	75.0	Parallel	8.2	0.835
lean,			13.8	0.814
leg,			20.9	0.773
Premium			23.6	0.762
Grade,			40.4	0.255
(2.1% fat)			47.2	0.260
			74.6	0.258
			106.4	0.254
			138.9	0.261
Lamb,	71.8	Perpendicular	5.6	0.650
lean,			11.8	0.623
leg,			17.0	0.607
Premium			23.9	0.590
Grade,			41.8	0.260
(8.7% fat)			51.0	0.259
			93.6	0.271
			115.6	0.271
			142.0	0.276
Lamb,	71.0	Parallel	6.0	0.735
lean,			10.1	0.730
leg,			19.3	0.689
Premium			24.8	0.679
Grade,			42.0	0.240
(9.6% fat)			50.8	0.226
			87.4	0.236
			119.3	0.243
			142.6	0.244

change structure (recrystallize) during frozen storage and in the early stages of thawing, it seems likely that this recrystallization would also affect the type and number of imperfections. Thus, differences in the freezing conditions might have influenced the thermal conductivity values.

The data obtained by this and previous investigations show that the conductivity measured parallel to the grain of the meat is higher than the conductivity measured perpendicular to the grain. This might be explained by the formation of the ice crystals during freezing, as mentioned above. Since the ice crystals tend to grow in a direction parallel to the fibers, it would appear that the crystalline structure would have a greater influence on the conductivity measured parallel to the grain than on the conductivity measured perpendicular to the grain.

Although an effort is made in this discussion to determine the relationship between thermal conductivity and type of meat, the conclusions cannot be completely justified because of insufficient data available at equivalent moisture and fat contents and because the relationship between conductivity and fat content is not known.

Between 22°F and 32°F the experimental data are not conclusive since the percentage of meat frozen varies with temperature in this region. It is estimated by Miller (7) that the percentage of meat frozen, and hence also the thermal conductivity, varies abruptly with temperature near 31°F. The data above 32°F, in all cases, apply to samples which were previously frozen.

From 80°F to 150°F, the curves are shown as dotted lines in order to indicate a degree of uncertainty in the accuracy of the moisture and fat contents assigned to the curves in this region. This uncertainty is because of the large weight loss that occurred during the conductivity measurements at these temperatures. The average weight loss of the samples was 19 per cent during the conductivity measurements in the region 32°F to 150°F.

Separate tests were conducted to determine the temperature at which the majority of the weight loss occurred, and the percentages of the weight loss due to moisture and fat losses. Two samples were cut from a large piece of fresh, inside round beef. The fat content of one sample was determined. The other sample was frozen, allowed to thaw, and held at a room temperature of approximately 80°F for four hours. The juices which drained from the beef during thawing were collected. The sample was weighed before and after the tests and showed a 6 per cent weight loss. The fat content of the sample was then measured and found to be identical with that of the fresh sample. Therefore, it was concluded that approximately two-thirds of the moisture loss and all of the fat loss occurred above 80°F in the conductivity tests.

It should be noted that there were definite indications that some of the fat was cooked out of the meat samples during the conductivity measurements at elevated temperatures. This was substantiated by comparing fat content measurements made on the samples which had been used for conductivity tests with fat content measurements made on fresh samples obtained from the same pieces of meat. In all cases, the fat content of the fresh samples was higher than the fat content of the samples which had been used in the conductivity tests.

It should be noted that the temperature scale used in the figures is expanded in the frozen region where the slope is varying and is contracted in the fresh region where the slope remains essentially constant.

Beef

The results obtained from the experimental investigation of beef are shown in Figures 7 through 10. The conductivity values are plotted in Figures 7 and 8 as a function of temperature and compared with results obtained by previous investigators. In Figure 9 the conductivity values are plotted as a function of temperature and compared with the values obtained from a mathematical model proposed by Miller and Sunderland (17). In summary, all available data for beef are plotted and compared in Figure 10.

In Figure 7 data are shown for conductivity for samples of beef which were cut so that the heat flow was parallel to the grain of the beef. Above freezing, the conductivity increases slightly as the temperature increases. Below freezing, the conductivity varies inversely with temperature. This variation of thermal conductivity with temperature follows the same trend as the thermal conductivity of ice and water (see Appendix). It was expected that the conductivity would be higher for samples having a higher moisture content. The data compare favorably in this respect with that obtained by Hill (5) and Miller (7), but seem to disagree with the values obtained by Lentz (6).

However, the method used by Lentz and Miller to determine thermal conductivity values was a guarded hot plate method similar to that specified by the ASTM, while that used by Hill and this investigator was a modified guarded hot plate method using a heat flow meter. In addition,

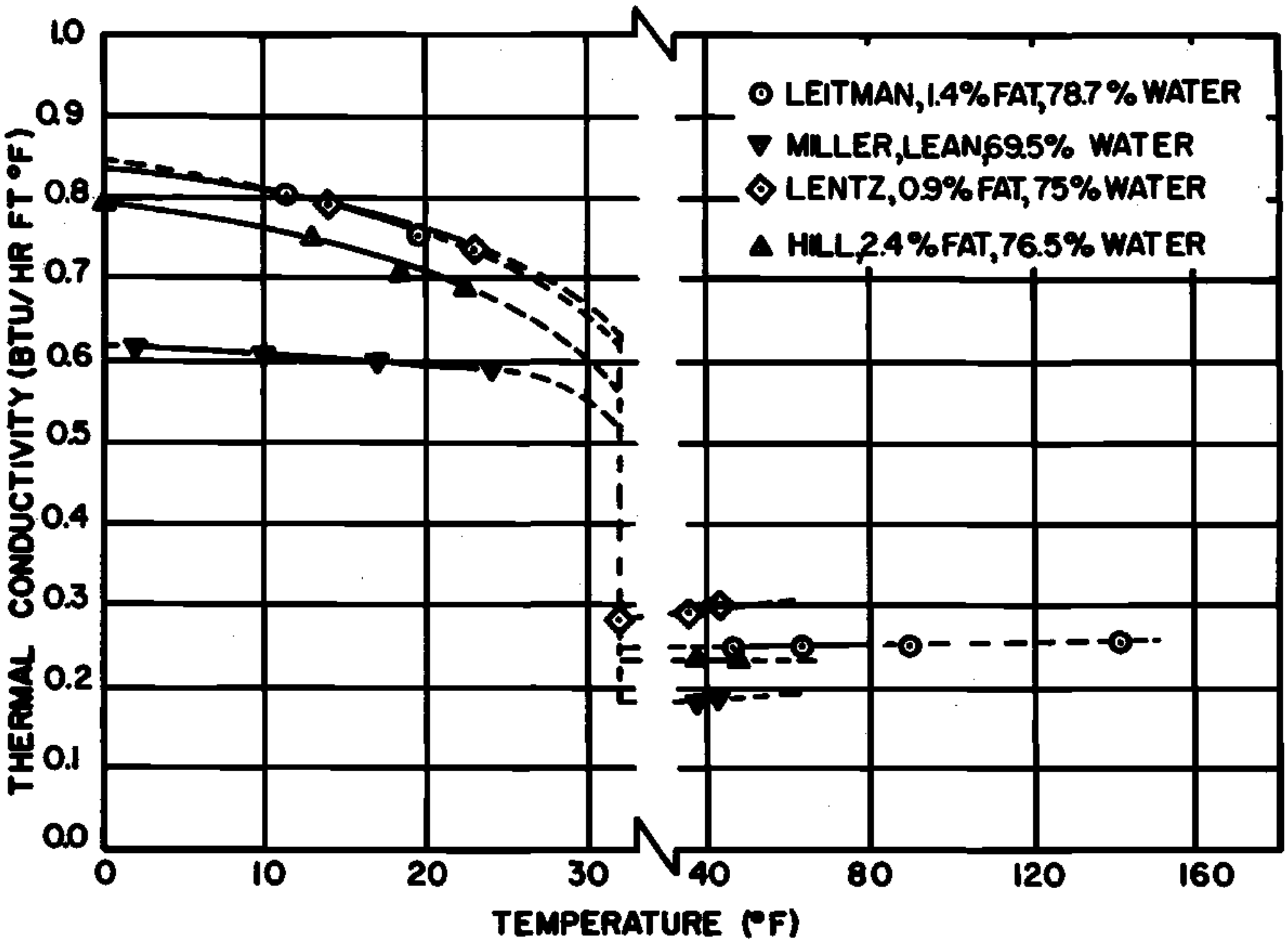


Figure 7. Thermal Conductivity versus Temperature for Lean Beef, Parallel to the Grain.

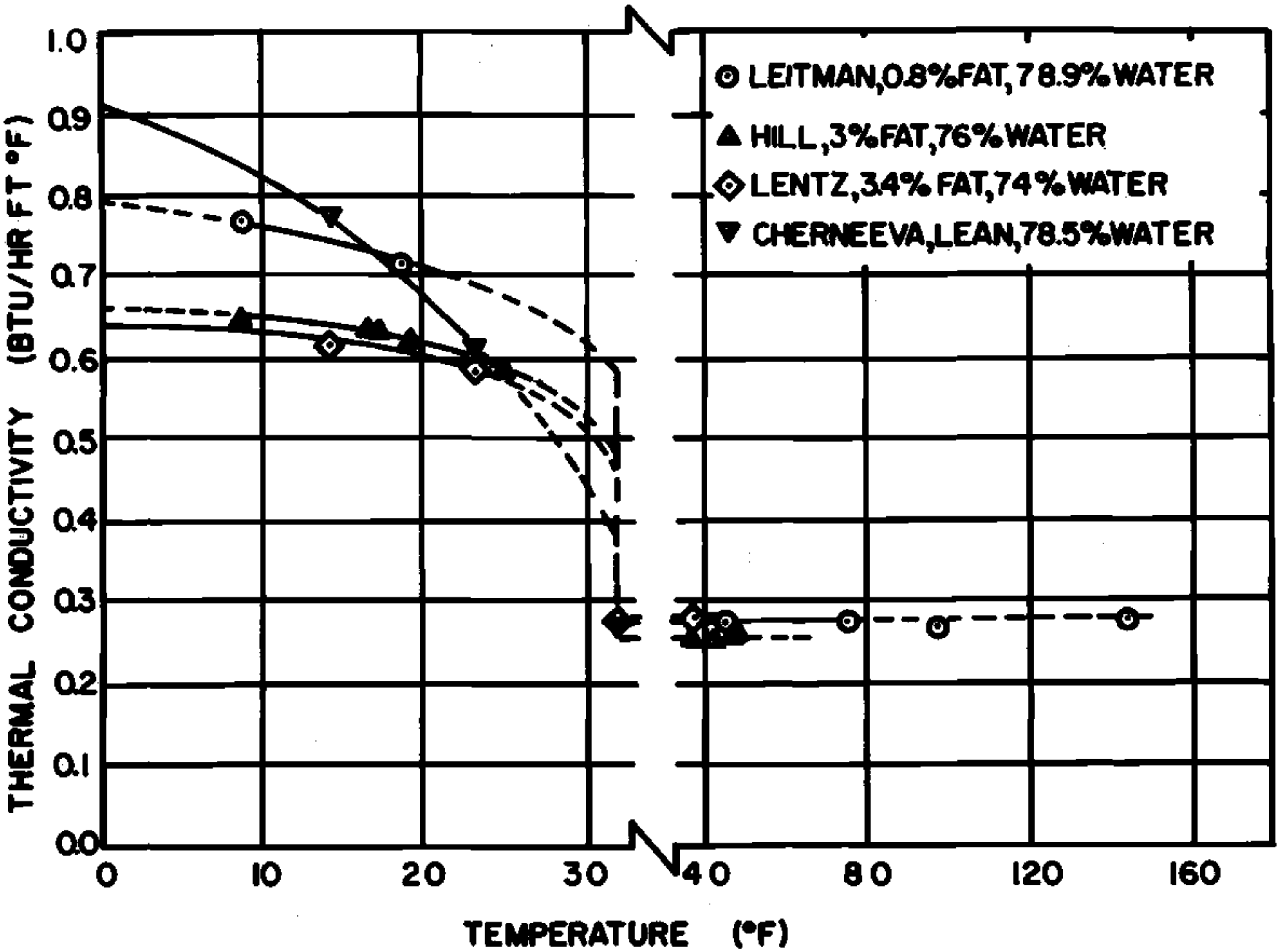


Figure 8. Thermal Conductivity versus Temperature for Lean Beef, Perpendicular to the Grain.

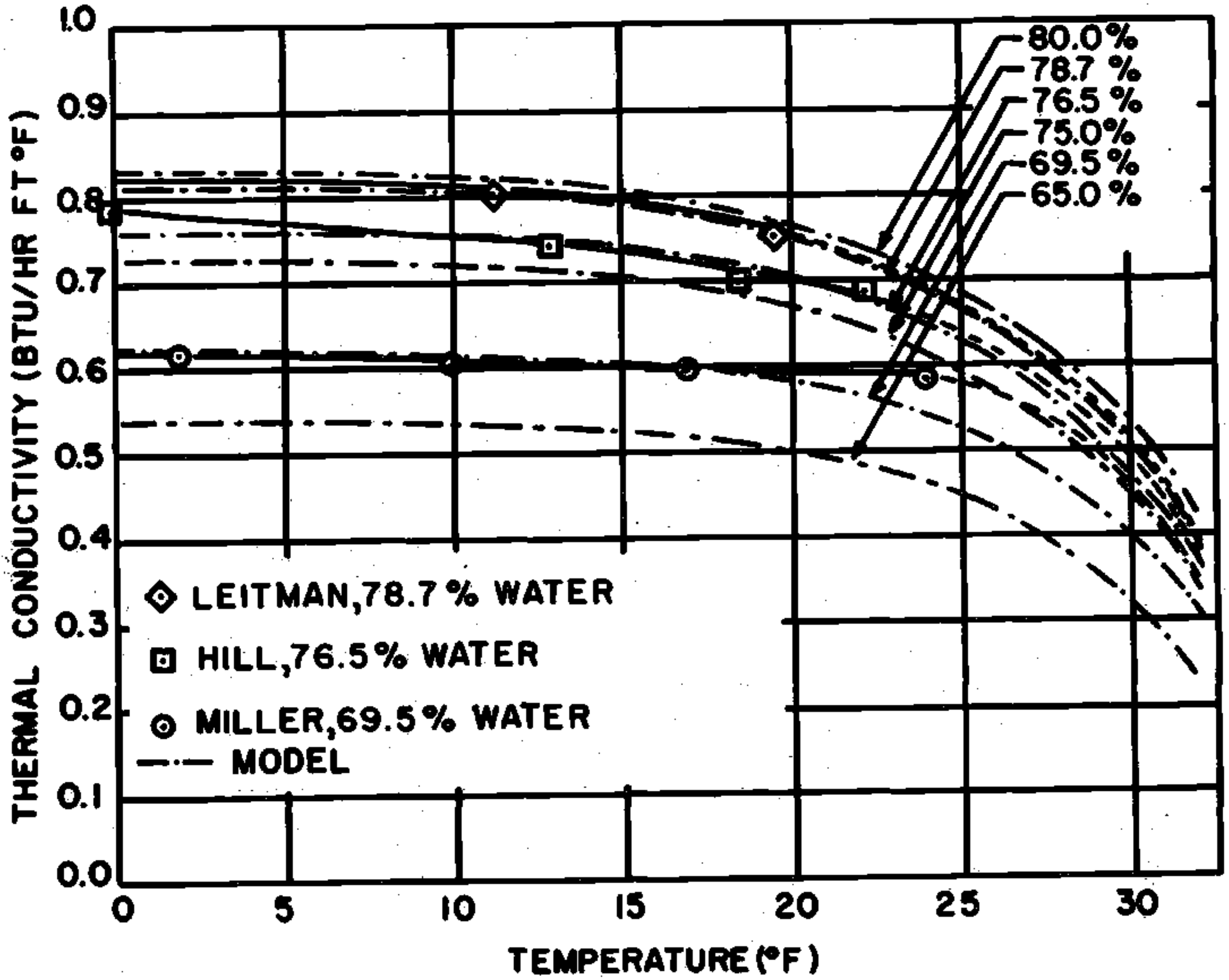


Figure 9. Thermal Conductivity versus Temperature for Lean Beef, Parallel to the Grain.

the sample used by Lentz was taken from lean, sirloin of beef, the sample used by Miller was from eye of loin beef, and those used by Hill and this investigator were from inside round beef. Also, Lentz's sample was frozen in the conductivity apparatus itself prior to testing, while the samples used by Hill, Miller, and this investigator were frozen in a domestic freezer. Miller's sample was aged for two weeks at 36°F in a room with high humidity prior to freezing.

In Figure 8 data are plotted for values of conductivity of samples of beef which were cut so that the heat flow was perpendicular to the grain of the beef. As in Figure 7, above freezing the conductivity increases slightly with temperature, while below freezing the conductivity varies inversely with temperature. The data are in agreement with that obtained by Hill and Lentz with the values of conductivity increasing with increasing moisture content, but seem to be in disagreement with the data of Cherneeva (4). However, the fat content and type of beef were not specified by Cherneeva, and this could explain the apparent disagreement.

Miller and Sunderland (17) present a mathematical model for predicting the thermal conductivity of beef in a direction parallel to the fiber for beef with a moisture content of 60 per cent or higher. This model is presented in the Appendix. The model will predict values of thermal conductivity as a function of moisture content. In Figure 9 data of this investigation, as well as data by Miller (7) and Hill (5), are plotted as a function of temperature and compared with the respective values calculated by using the model. As can be seen, there is excellent agreement in the frozen region from 0 to 22°F. Values of conductivity predicted by the model at other moisture contents are provided for reference. For a moisture content of 75 per cent, the model predicts values of thermal conductivity 11 per cent lower than the measurements made by Lentz (6) in the temperature range 0 to 22°F. The model seems to work very well in the frozen region, and should aid in predicting values of thermal conductivity.

All available data for the thermal conductivity of nondehydrated beef are presented in Figure 10 which is a combination of Figures 7 and 8. It can be seen that all of the curves show the same variation of conductivity with temperature. For this investigation, the conductivity of the sample for heat flow parallel to the grain is approximately 8 per cent higher than the conductivity of the sample with heat flow perpendicular to the grain. This difference might be caused by the growth of the ice crystals along the fibers, as mentioned previously.

The corresponding difference between conductivity values measured parallel and perpendicular to the grain obtained by Hill (5) is approximately 16 per cent, while that obtained by Lentz (6) is approximately 22 per cent. There are several possible reasons for this apparent disagreement. The method used by Lentz was different from that used by Hill and this investigator. The samples used by Lentz were obtained from different cuts of beef at different moisture and fat contents than those used by Hill or this investigator. In addition, Lentz's data for the two cases of perpendicular and parallel heat flow were obtained from different cuts of beef at different moisture and fat contents. The sample with heat flow parallel to the grain was from lean, sirloin of beef at 75 per cent moisture and 0.9 per cent fat, while the other

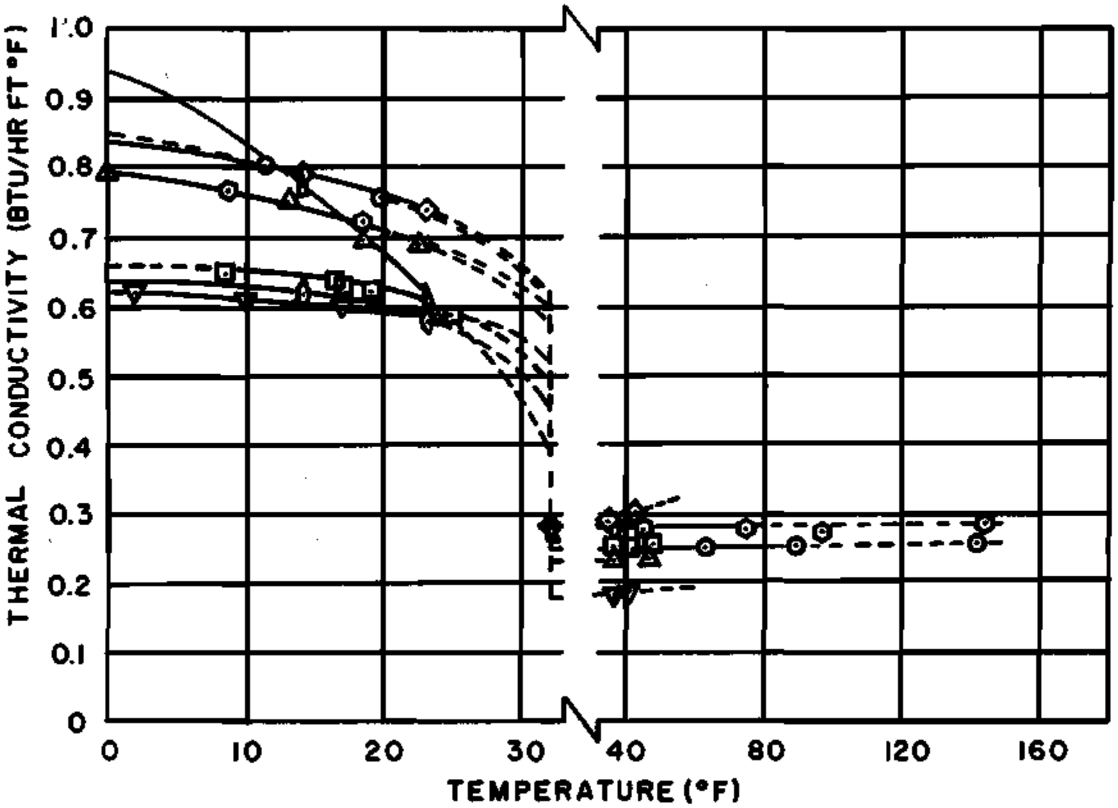


Figure 10. Thermal Conductivity versus Temperature for Lean Beef.

LEGEND:

⊙ LEITMAN, 1.4% FAT, 78.7% WATER, ∥ TO THE GRAIN

◇ LENTZ, 0.9% FAT, 75% WATER, ∥ TO THE GRAIN

△ HILL, 2.4% FAT, 76.5% WATER, ∥ TO THE GRAIN

▽ MILLER, LEAN, 69.5% WATER, ∥ TO THE GRAIN

⊡ HILL, 3% FAT, 76% WATER, ⊥ TO THE GRAIN

⊙ LEITMAN, 0.8% FAT, 78.9% WATER, ⊥ TO THE GRAIN

⊖ LENTZ, 3.4% FAT, 74% WATER, ⊥ TO THE GRAIN

▲ CHERNEEVA, LEAN, 78.5% WATER, ⊥ TO THE GRAIN sample was from lean, flank beef at 74 per cent moisture and 3.4 per cent fat.

Samples used by Hill and this investigator were from the same cut of beef, inside round, but with different moisture and fat contents. However, for both investigations, the data for the two cases of heat flow were obtained from samples having approximately equal moisture and fat contents.

As previously mentioned, the freezing rate, freezing temperature, and frozen storage time involved in the freezing process prior to the conductivity measurements might have influenced the data. The samples used by Lentz were frozen in the conductivity apparatus itself in 2-4 hours. The samples used by Hill were frozen for approximately two weeks in a domestic freezer. The samples used in this investigation were also frozen in a domestic freezer but for only two days. In addition, the samples might have been subjected to different freezing temperatures and rates which could have influenced the conductivity values.

Pork

The results obtained from the experimental investigation of pork are shown in Figure 11, together with all available data from previous investigations. The conductivity values for samples of pork with heat flow parallel to the grain and the values for samples with heat flow perpendicular to the grain are plotted as a function of temperature and compared with results obtained by previous investigators. Again, above freezing the conductivity increases with temperature, while below freezing the conductivity varies inversely with temperature. In the

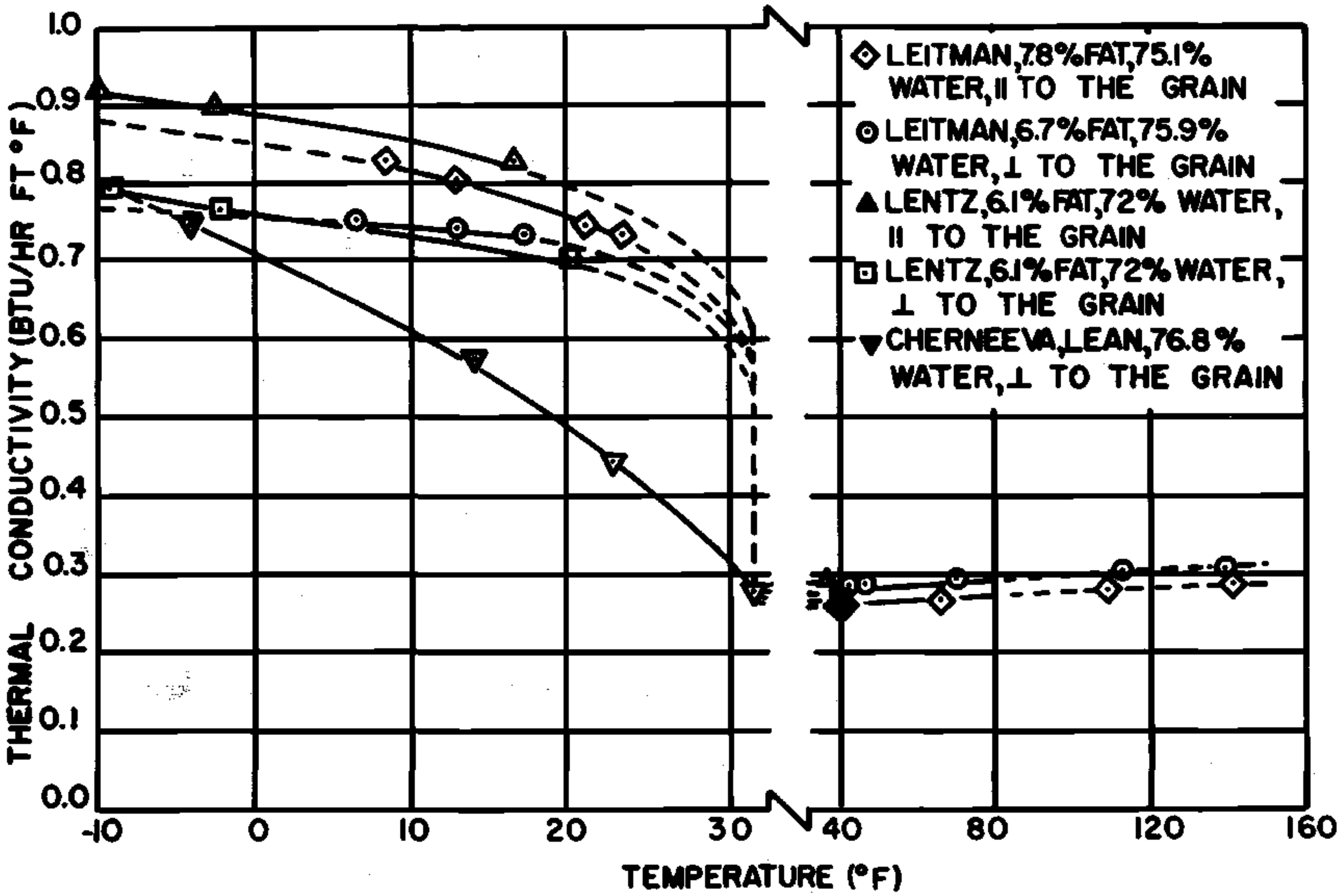


Figure 11. Thermal Conductivity versus Temperature for Lean Pork.

frozen region, the conductivity of the sample measured parallel to the grain is approximately 10 per cent higher than the conductivity of the sample measured perpendicular to the grain. The corresponding difference obtained by Lentz (6) was 17 per cent. It was expected that the conductivity would be higher for samples having a higher moisture content. However, the data of this investigation seem to disagree in this respect with the data obtained by Lentz (6) and Cherneeva (4). Here again, possible differences in test methods, freezing conditions, and type of pork might explain the disagreement.

A comparison of conductivity values for pork of this investigation with those presented for beef in Figure 10 would seem to indicate that the conductivity of pork is higher for both cases (perpendicular and parallel to the grain) than the conductivity of beef for comparative moisture contents. It can be seen that the data obtained by Lentz also support this conclusion. However, there are insufficient data available for beef and pork at equivalent moisture and fat contents to justify this conclusion completely.

Veal

The results obtained from the experimental investigation of veal are shown in Figure 12. Values of conductivity measured perpendicular and parallel to the grain are plotted as a function of temperature. There are no previous data with which to compare the results of this investigation. As expected, the conductivity increases with temperature in the region above freezing, while the conductivity varies inversely with temperature in the frozen region. In the frozen region, it can be seen that the conductivity measured parallel to the grain is approximately 8 per cent higher than the conductivity measured perpendicular to the grain. This is the same difference observed for the beef data. A comparison of the veal data of Figure 12 with the beef data of Figure 10 and pork data of Figure 11 would seem to indicate that the conductivity of veal is higher for both cases (perpendicular and parallel to the grain) than the conductivity of pork and beef for comparative moisture contents. Again, there are insufficient data available for beef, pork, and veal at equivalent moisture contents for a complete justification of the above statement.

Lamb

The results obtained from the experimental investigation of lamb are shown in Figure 13. Values of conductivity measured perpendicular and parallel to the grain are plotted as a function of temperature. There are no previous data available with which to compare the results of this investigation. The lamb samples followed the same trends observed for beef, pork, and veal; that is, an increase of conductivity with temperature in the fresh region and an inverse variation of conductivity with temperature in the frozen region. It can be seen that the conductivity of the lamb samples with heat flow parallel to the fibers is approximately 14 per cent higher than the conductivity of the samples with heat flow perpendicular to the fibers. However, it should be noted that there was a moisture content difference of approximately 1 per cent between the two samples. A comparison of the conductivity values for lamb at 71 per cent moisture with parallel heat flow

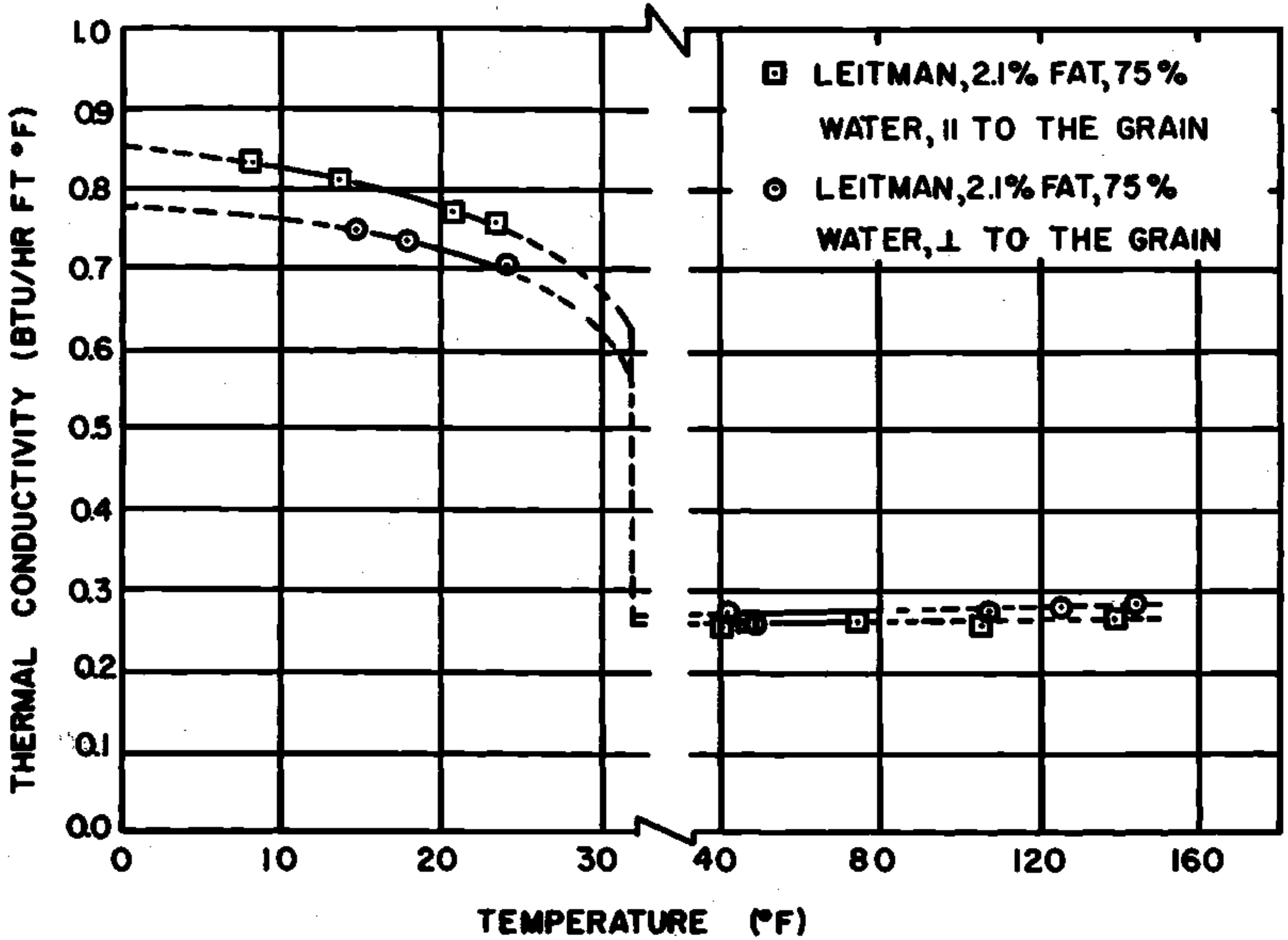


Figure 12. Thermal Conductivity versus Temperature for Lean Veal.

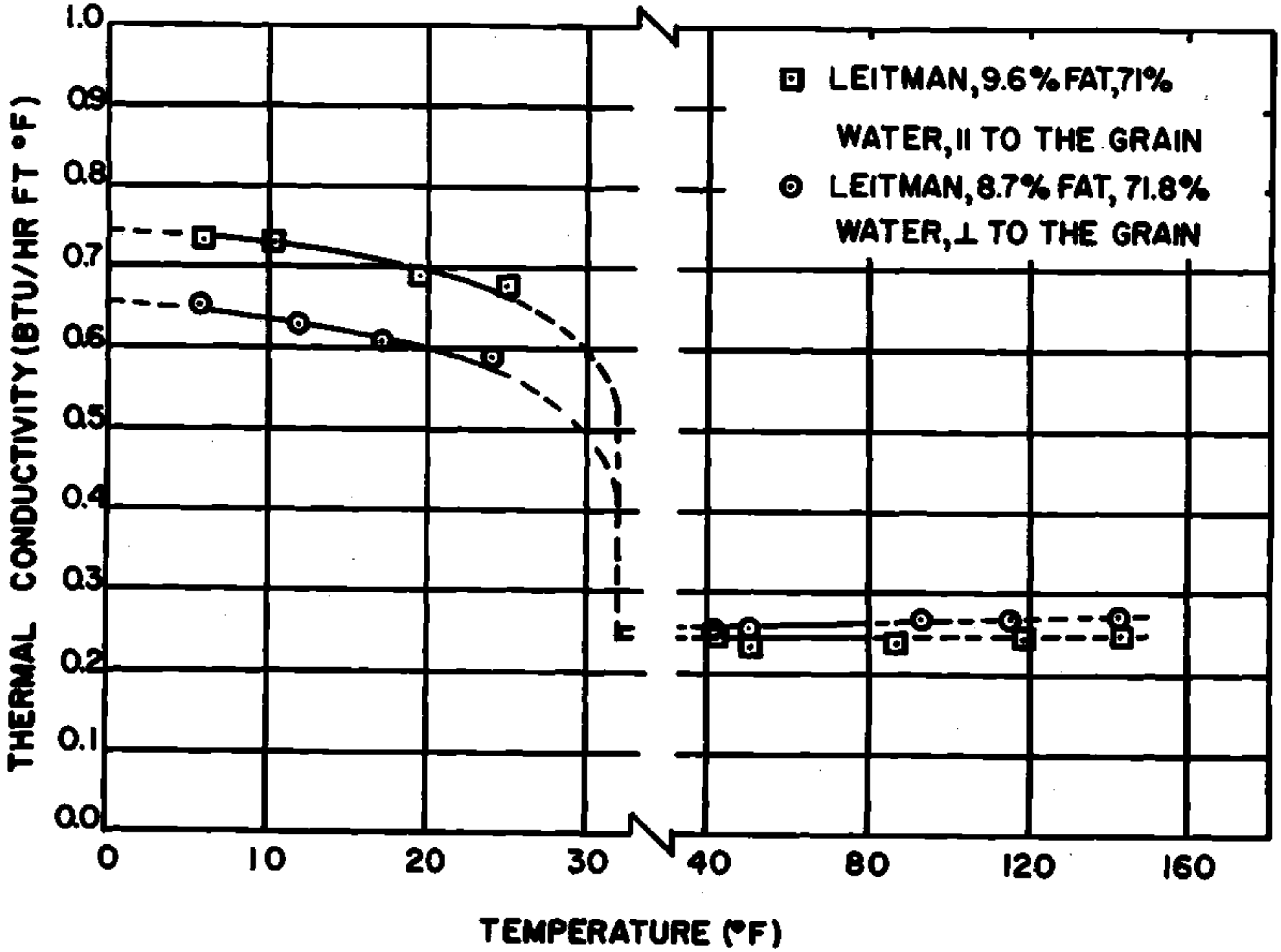


Figure 13. Thermal Conductivity versus Temperature for Lean Lamb.

with Miller's data (7) for beef at 69.5 per cent moisture in Figure 10 would tend to indicate that the conductivity of lamb is higher than that of beef.

Closure

The results obtained from this investigation provide additional data on the thermal conductivity of beef and pork, and provide previously unavailable data on the conductivity of veal and lamb. The results seem to agree with previous investigations by Hill (5) and Miller (7), but seem to disagree to some extent with the investigations of Lentz (6) and Cherneeva (4). Possible explanations for the apparent disagreement between investigations were mentioned, but it should be emphasized again that the explanations are hypothetical. The preceding discussion points out the definite need for additional investigations on all the meats at several moisture contents with an objective towards resolving the disagreements between the investigations.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

The results obtained from this investigation of the thermal conductivity of meats lead to the following conclusions:

1. In the frozen region (0°F to 22°F), for both heat flow perpendicular and parallel to the grain of the fiber, the thermal conductivities of beef, pork, veal, and lamb vary inversely with temperature.

2. In the fresh region, for both heat flow perpendicular and parallel to the grain of the fiber, the thermal conductivities of beef, porl, veal, and lamb increase slightly with temperature.

3. In the frozen region, the thermal conductivities of beef, pork, veal, and lamb will be higher with heat flow in a direction parallel to the fiber than with heat flow in a direction perpendicular to the fiber.

4. The thermal conductivity of beef in a given direction will be higher for samples having higher moisture contents.

5. Between 22°F and 32°F, the experimental data are not conclusive since the percentage of meat frozen varies with temperature in this region.

6. The mathematical model presented by Miller and Sunderland (20) is very useful in predicting the thermal conductivity of beef from 0 to 22°F in a direction parallel to the fiber and for beef with a

moisture content of 60 per cent or higher.

In addition to the above conclusions, the results obtained from this investigation indicate certain trends regarding the thermal conductivity of meats. However, it should be noted that the following trends cannot be completely justified because of the insufficient data available for meats.

1. The thermal conductivities of pork, veal, and lamb in a given direction, like beef, will be higher for samples having higher moisture contents.

2. At elevated temperatures (80°F to 150°F), the thermal conductivities of beef, pork, veal, and lamb increase slightly with temperature.

3. In the frozen region, the thermal conductivity of pork for both directions of heat flow (perpendicular and parallel to the grain) is higher than the conductivity of beef at equivalent moisture contents.

4. In the frozen region, the thermal conductivity of veal is higher for both directions of heat flow than the conductivities of beef and pork for equivalent moisture contents.

5. In the frozen region, the thermal conductivity of lamb is higher than the thermal conductivity of beef for heat flow in a direction parallel to the fiber and at equivalent moisture contents. It is expected that this trend would also be observed for heat flow in the perpendicular direction if sufficient data were available.

The following items are recommended as a logical extension of this investigation:

1. Data should be taken on samples in the unfrozen region both before and after freezing to verify that the conductivity does not depend upon whether the meat was previously frozen.

2. A study should be made to determine the relationship between thermal conductivity and fat content.

3. Additional data should be obtained for beef, pork, veal, and lamb at several moisture contents in order to verify the trends expressed above.

4. Additional data should be obtained for different cuts of meat (loin, rib, shoulder, etc.) to determine the dependence, if any, of thermal conductivity on cut of meat.

APPENDIX

STRUCTURAL MODEL FOR MEAT

In order to extrapolate the experimental results of the thermal conductivity of beef muscle for different moisture contents, Miller and Sunderland (17) proposed that the model in Figure 14 could be used. The model is made up of fibers arranged parallel and normal to the heat flow path; the remaining space is assumed to be filled with water or ice. The model has three parallel paths for heat transfer. The first path is composed only of fibers; the second path is water (or ice); the third path is a series arrangement of water (or ice) and fibers. It is assumed that no energy crosses the boundaries between the paths and that heat is transferred only by thermal conduction. The equivalent electrical circuit of the three paths is shown in Figure 15.

Consider an area equal to P^2 which lies in a plane perpendicular to the direction of heat transfer. If the total sample thickness is Δx, the thickness of each layer of fibers (P) equals $\frac{\Delta x}{n}$, where n is the number of fiber layers. The temperature drop across each layer of the fibers is $\frac{\Delta T}{n}$, where ΔT is the temperature difference across the sample. The rate of heat conduction through the fibers (q_1) is given by:

$$q_1 = k_f \, d_1 (2P - d_1) \frac{\Delta T}{nP}$$

where k_f is the thermal conductivity of the fibers. The rate of heat

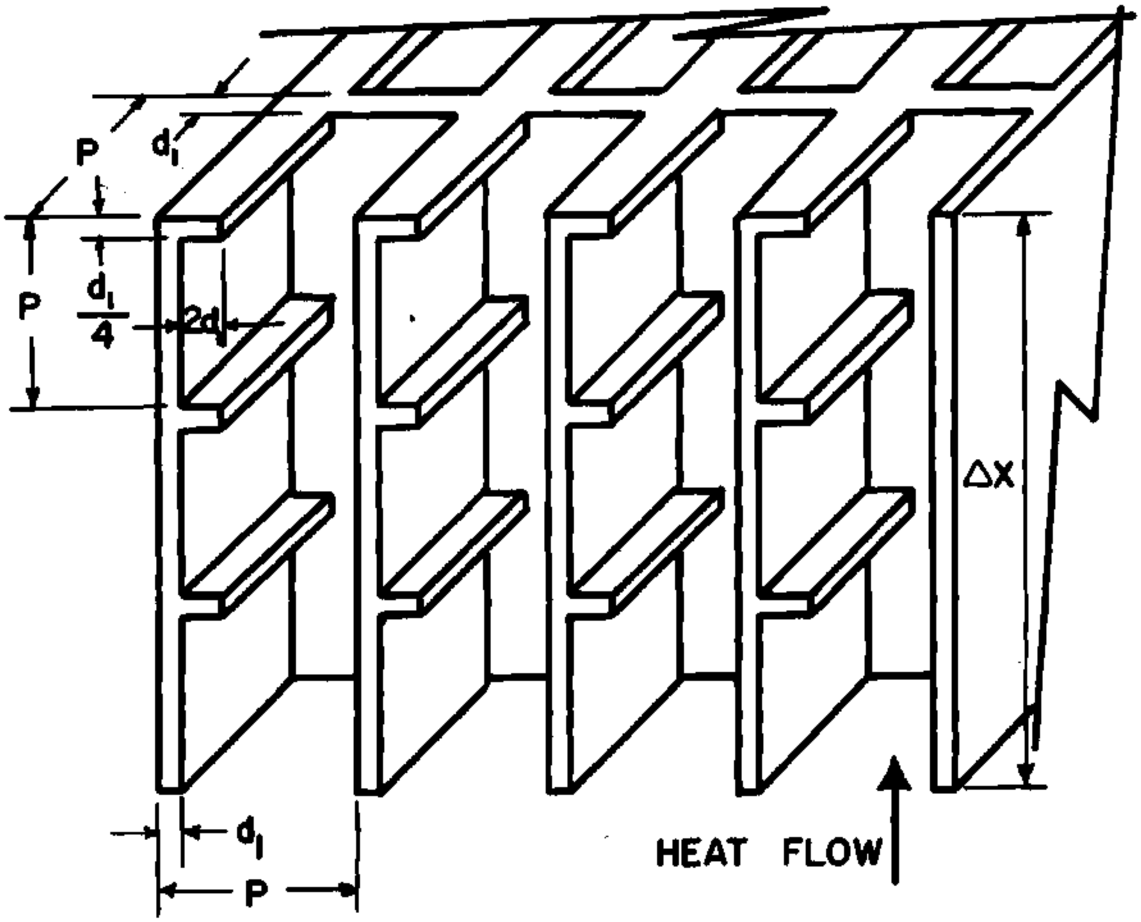


Figure 14. One Dimensional Thermal Conductivity Model for Meat.

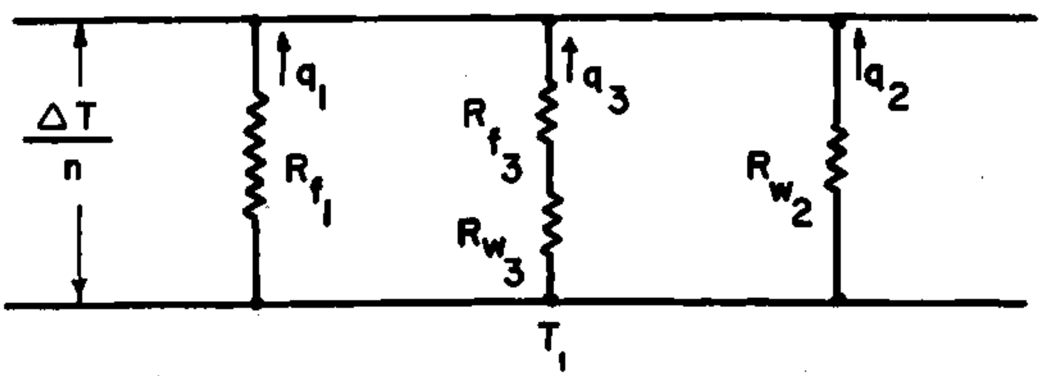


Figure 15. Analog of Heat Flow Paths Through Structural Model for Meat.

conduction through the water and/or ice (q_2) is:

$$q_2 = k_w[(P - d_1)^2 - 2d_1(P - d_1)] \frac{\Delta T}{nP}$$

or

$$q_2 = k_w[P^2 - 4Pd_1 + 3d_1{}^2] \frac{\Delta T}{nP}$$

where k_w is the thermal conductivity of the water or ice. The rate of heat conduction through the water and/or ice in series with the fiber (q_3) is given by:

$$q_3 = k_{fw}[2d_1(P - d_1)] \frac{\Delta T}{nP}$$

where:

$$k_{fw} = \frac{4k_f k_w}{\frac{d_1}{P} k_w + (4 - \frac{d_1}{P}) k_f}$$

The apparent thermal conductivity, k_a, is given by:

$$k_a = A \frac{q_1 + q_2 + q_3}{P^2 \frac{\Delta T}{\Delta x}}$$

Therefore it follows that:

$$k_a = k_f[2 \frac{d_1}{P} - (\frac{d_1}{P})^2] + k_w[1 - 4 \frac{d_1}{P} + 3(\frac{d_1}{P})^2] + \frac{8 k_f k_w[\frac{d_1}{P} - (\frac{d_1}{P})^2]}{\frac{d_1}{P} k_w + (4 - \frac{d_1}{P})k_f}$$

The volume of one of the cubes (V_T) of the model is given by the sum of the fiber volume (V_f) and the water volume (V_w). That is,

$$V_T = V_f + V_w = P^3$$

From Figure 14 it can be seen that:

$$V_f = 2d_1P^2 - 1/2\ d_1^{\ 2}\ P - \frac{d_1^{\ 3}}{2}$$

Since d_1 is very small compared with P, the last term of the previous equation can be neglected. Therefore:

$$\frac{d_1}{P} = 2 - \sqrt{4 - 2V_f/V_T}$$

The negative sign must be used in front of the square root because $\frac{d_1}{P}$ is always less than one.

Since the density of fresh meat (63 lbs/ft^3) is nearly equal to the density of the fiber shown in the model (64.2 lbm/ft^3), they are assumed equal. The ratio $\frac{d_1}{P}$ can then be expressed in terms of the total weight and the fiber weight. Thus:

$$\frac{d_1}{P} = 2 - \sqrt{4 - 2\ W_f/W_T}$$

Results of the calculations of the thermal conductivity based on the model for the beef with several moisture contents are tabulated in Table 3. These results are compared with experimental data in Figure 9.

Table 3. Thermal Conductivity of Nondehydrated Beef Predicted by the Model

Percent Moisture	Temperature °F	Conductivity $\frac{\text{Btu}}{\text{Hr °F Ft}}$
65.0	0	0.541
	5	0.541
	10	0.533
	15	0.524
	20	0.500
	25	0.450
69.5	0	0.623
	5	0.623
	10	0.615
	15	0.602
	20	0.576
	25	0.520
75.0	0	0.731
	5	0.731
	10	0.721
	15	0.709
	20	0.676
	25	0.595
76.5	0	0.764
	5	0.764
	10	0.755
	15	0.737
	20	0.706
	25	0.630
78.7	0	0.812
	5	0.812
	10	0.801
	15	0.787
	20	0.752
	25	0.670
80.0	0	0.835
	5	0.835
	10	0.823
	15	0.809
	20	0.769
	25	0.683

Harper and Chichester (3) report the thermal conductivity of meat fiber to be 0.0216 Btu/hr ft °F; in this thesis, the conductivity of meat fiber is assumed to be independent of temperature. The liquid phase is an aqueous solution which contains dissolved salts and proteins. The exact composition of this liquid phase is unknown. The conductivity values used here will be those of a 0.28 M salt solution shown in Figure 16, which have been reported by Long (18). As can be seen from the figure, the conductivity of the salt solution gradually decreases in the freezing region (22 to 32°F) as does beef. This is in contrast to the finite jump in the conductivity of distilled water at 32°F.

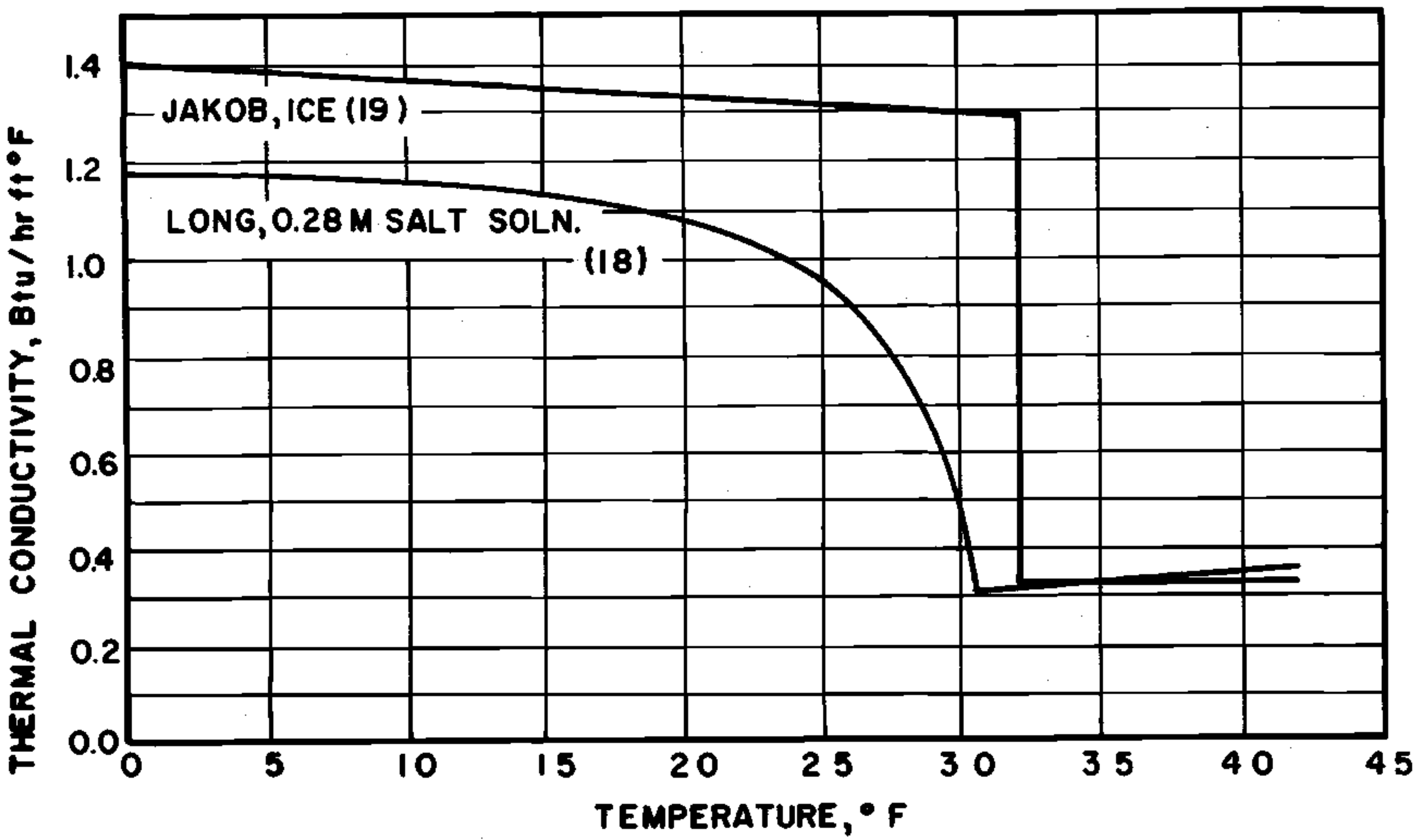


Figure 16. Thermal Conductivity versus Temperature for a Salt Solution and Ice.

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